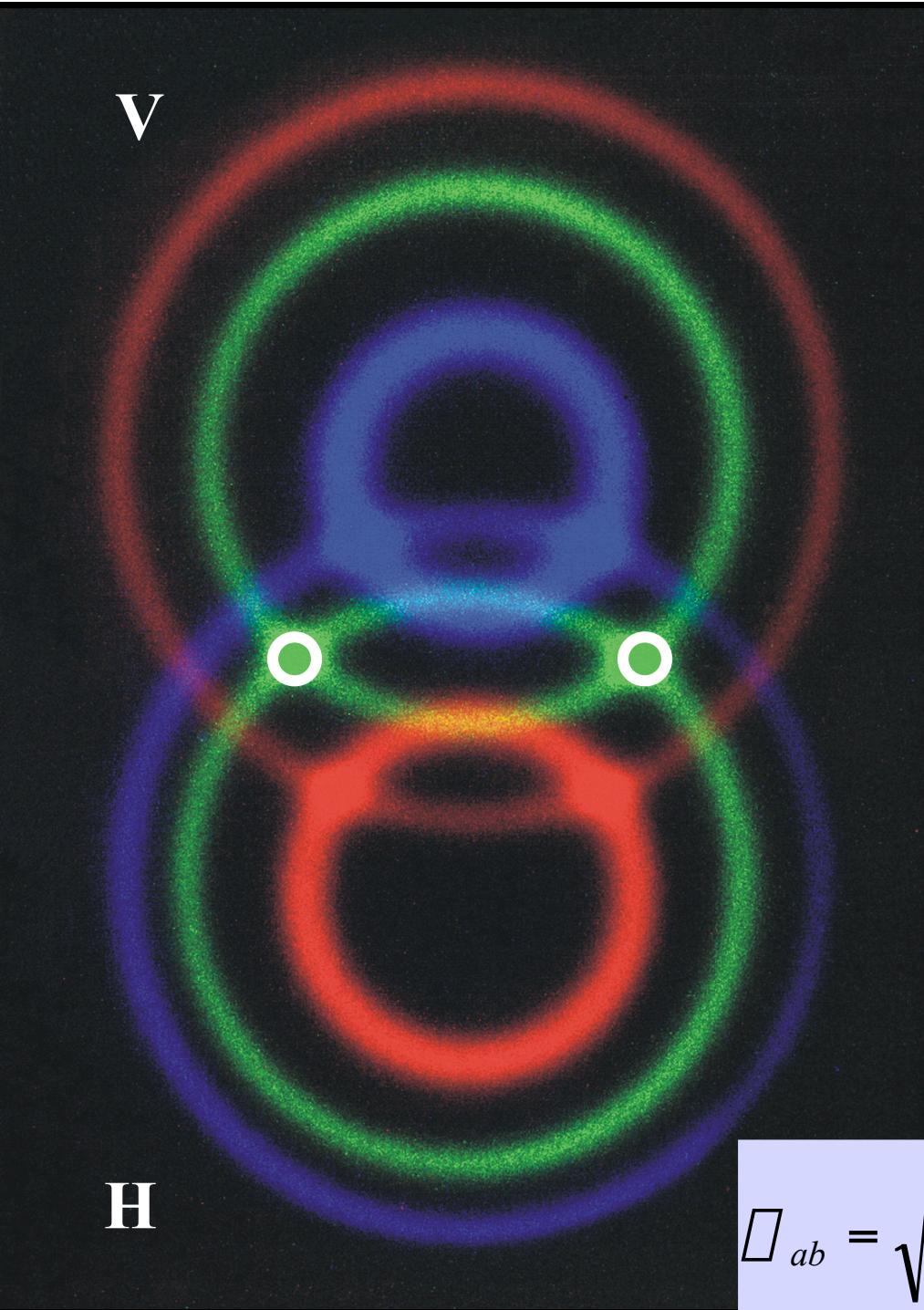


Exploring Multi-Photon Entanglement

Dirk Bouwmeester

Department of Physics
University of California
Santa Barbara

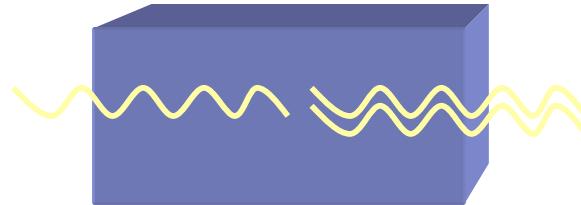
QUIM 2002



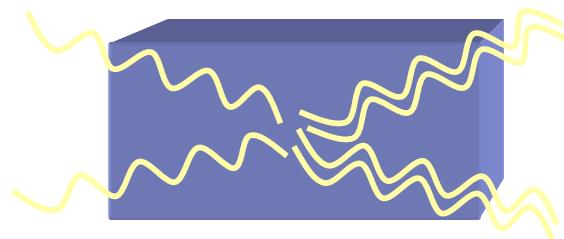
H

$$\square_{ab} = \sqrt{\frac{1}{2}}(H_a V_b \square V_a H_b)$$

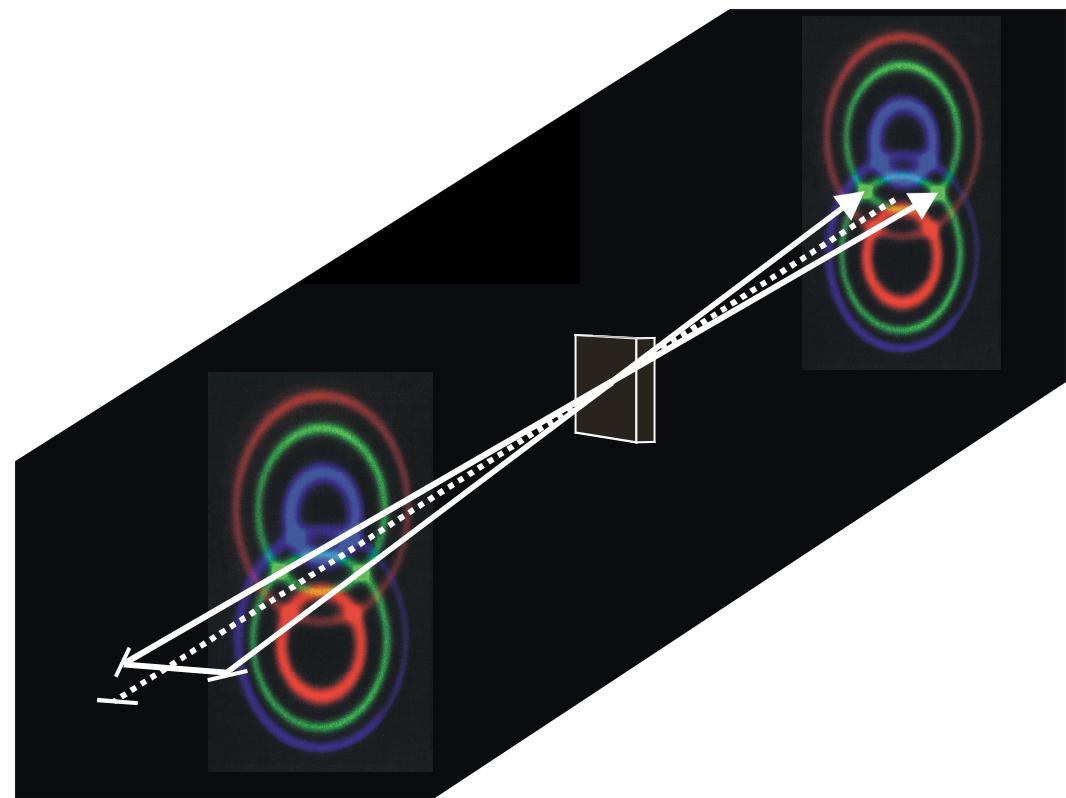
Towards an entangled-photon laser



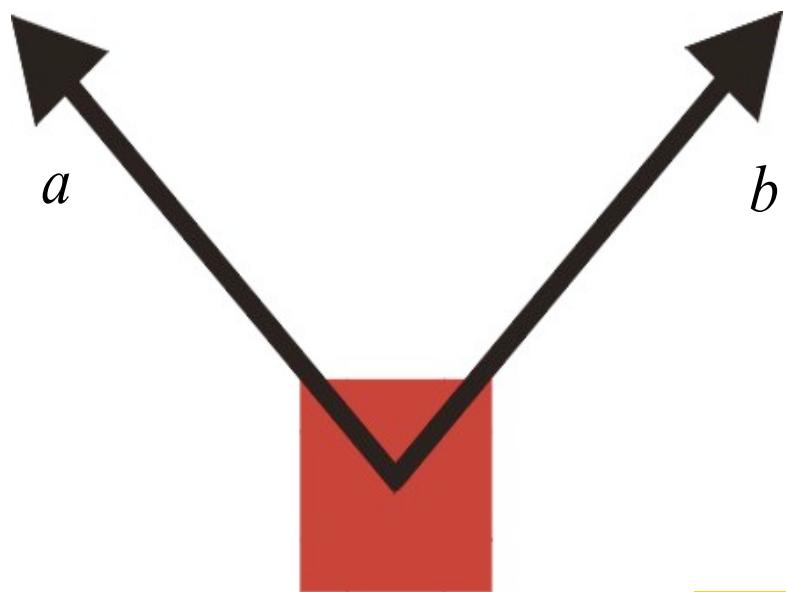
Stimulated emission of photons



Stimulated emission of entangled-photon pairs



Stimulated emission of polarization entangled photons



$$|N_H\rangle_a |N_V\rangle_a$$

$$|N_H\rangle_b |N_V\rangle_b$$

$$U(t) = e^{\frac{i}{\hbar} H t} = e^{i \frac{t}{\hbar} L_+^\dagger L_-}$$

$$\square \equiv \frac{it}{\hbar},$$

$$L_+ \equiv a_V^\dagger b_H^\dagger - a_H^\dagger b_V^\dagger,$$

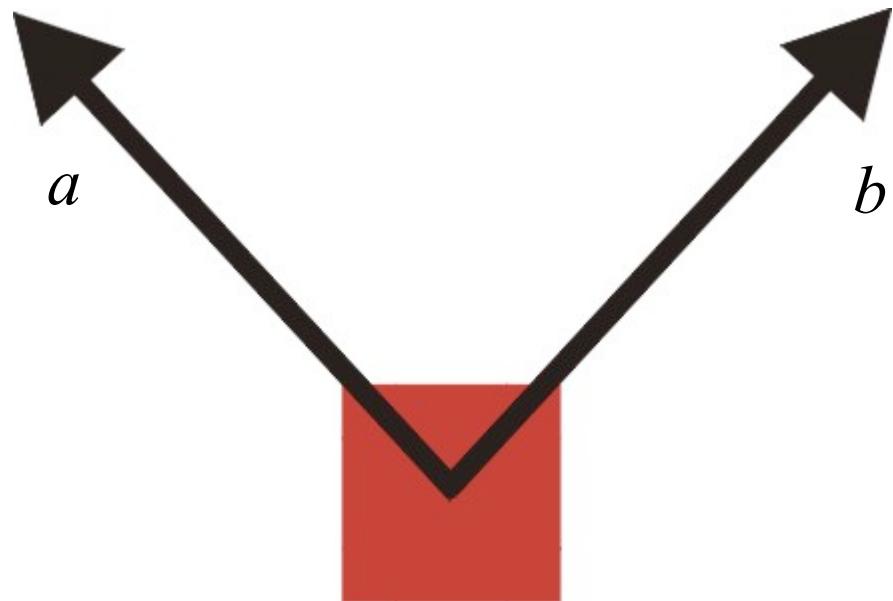
$$L_- = L_+^\dagger$$

$$|\square\rangle = \prod_{n=0} \square^n \prod_{k=0}^n (1)^k |n \square k, k; k, n \square k\rangle$$

$$\prod_{n=0} \square' \begin{array}{c} n \\ \square \\ k=0 \end{array} (\square 1)^k |n \square k, k; k, n \square k \rangle \begin{array}{c} \square \\ \square \end{array}$$

$$n = 0$$

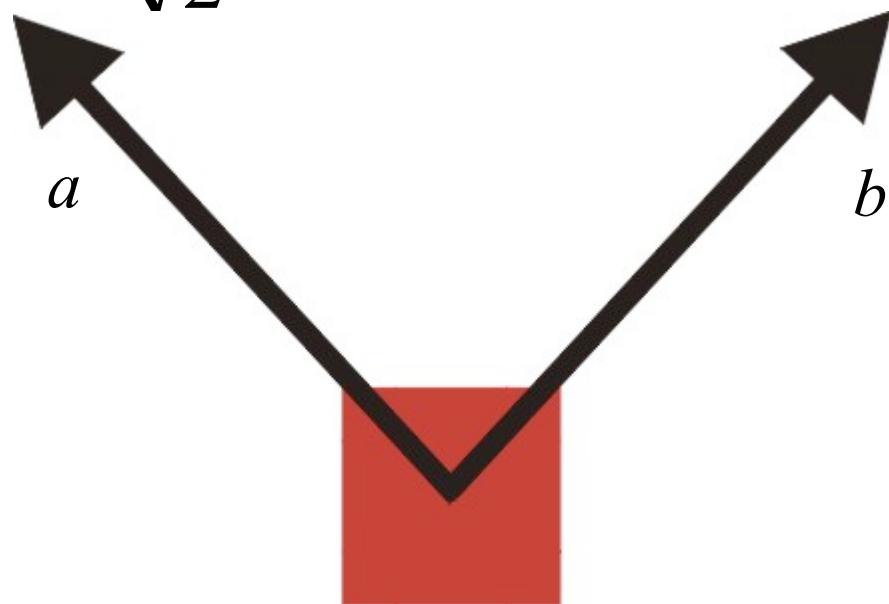
$$|0,0;0,0\rangle$$



$$\prod_{n=0}^{\infty} \prod_{k=0}^n \left(\frac{1}{k!} \right)^k |n \square k, k; k, n \square k \rangle$$

$$n = 1$$

$$\frac{1}{\sqrt{2}} (|1,0;01\rangle \square |0,1;10\rangle)$$



$$\prod_{n=0}^{\infty} \prod_{k=0}^n (\square_1)^k |n \square k, k; k, n \square k\rangle$$

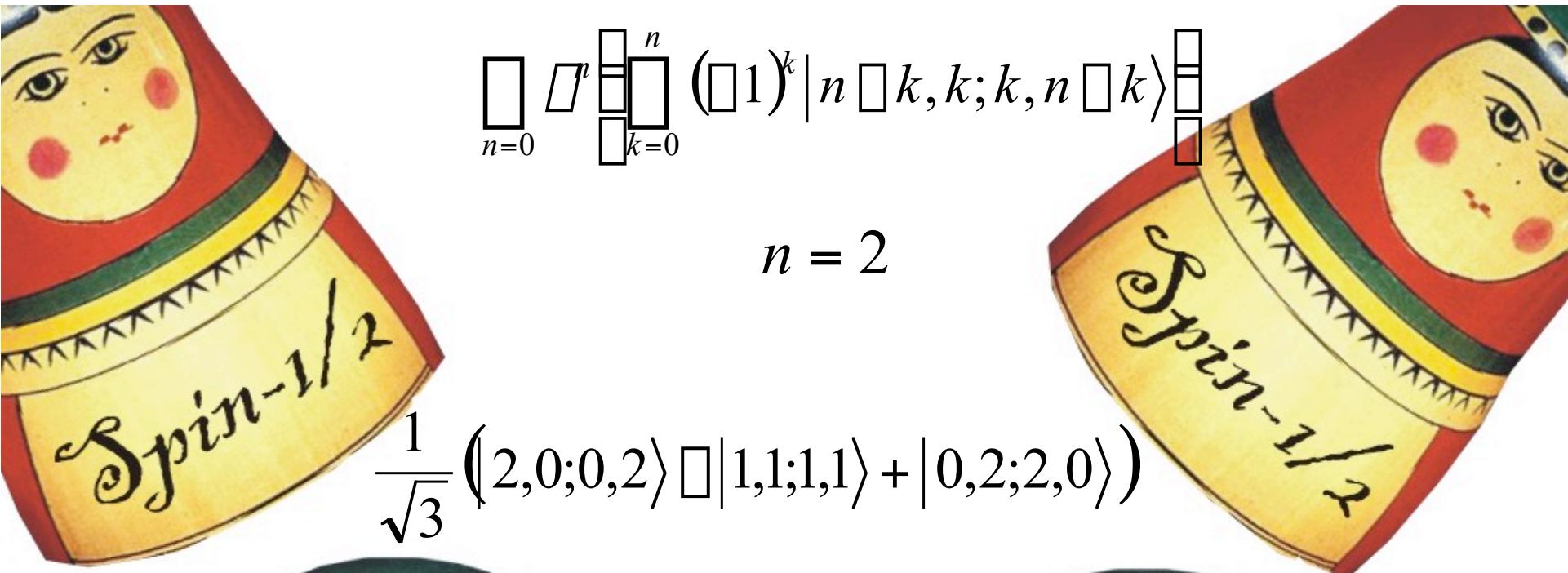
$$n = 1$$

$$\frac{1}{\sqrt{2}} (\langle 1,0;0,1 \rangle \square |0,1;1,0 \rangle)$$



Singlet




$$\prod_{n=0}^{\infty} \prod_{k=0}^n (\Box 1)^k |n \Box k, k; k, n \Box k \rangle$$

$$n = 2$$

$$\frac{1}{\sqrt{3}} (|2,0;0,2\rangle \Box |1,1;1,1\rangle + |0,2;2,0\rangle)$$

$$|1,\Box 1\rangle \Box |0,0\rangle + |\Box 1;1\rangle$$

Singlet



$$\left| \begin{array}{c} \square \\ n=0 \end{array} \right\rangle \left| \begin{array}{c} \square' \\ k=0 \end{array} \right\rangle \left| \begin{array}{c} \square \\ n \end{array} \right\rangle \left(\square | 1 \rangle \right)^k \left| \begin{array}{c} \square \\ k, k; k, n \end{array} \right\rangle \left| \begin{array}{c} \square \\ \square \end{array} \right\rangle$$



$n = 1$



$n = 2$



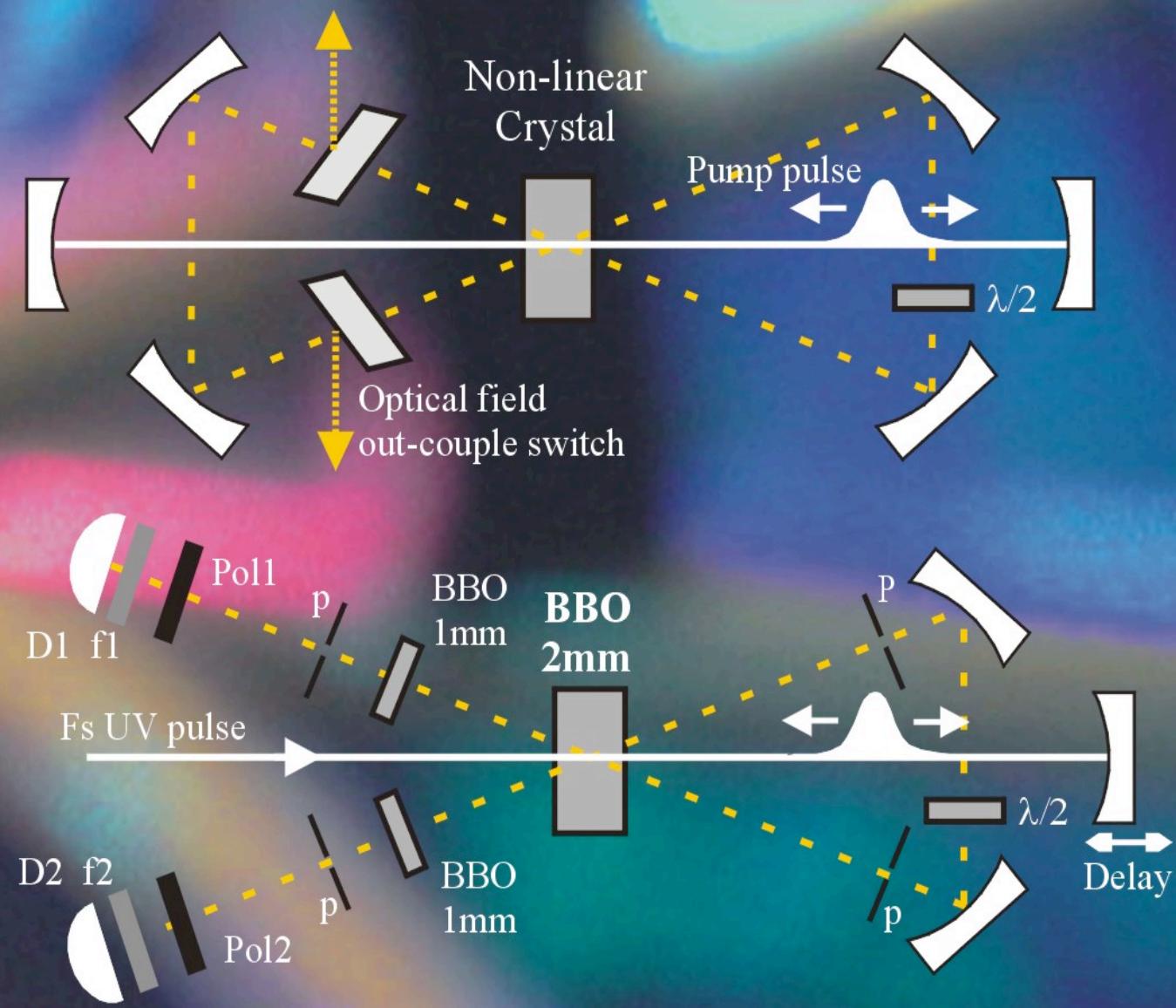
Singlet



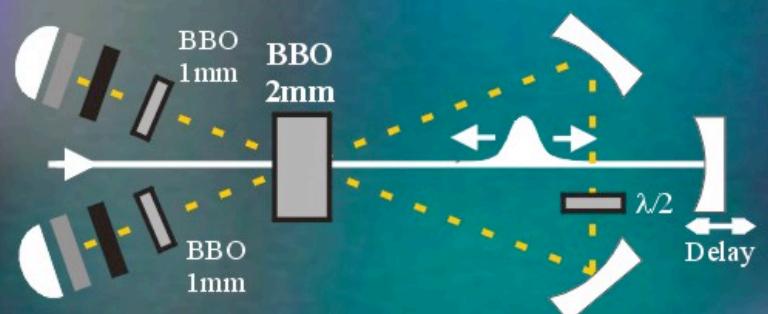
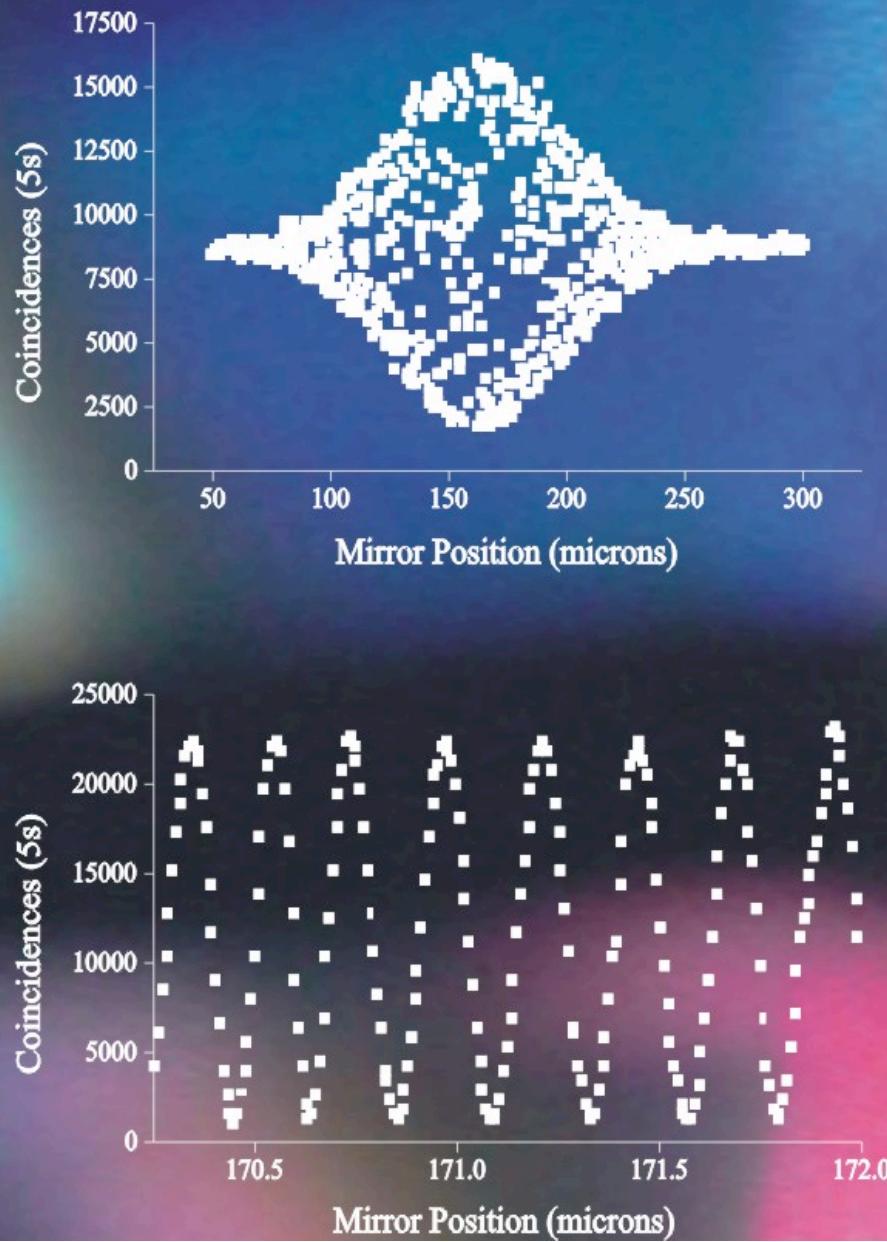
• • •

$n = k$

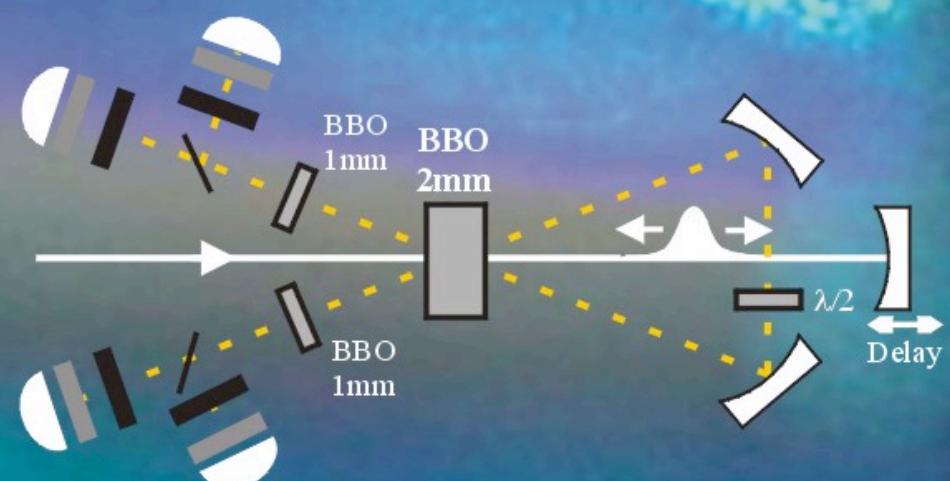
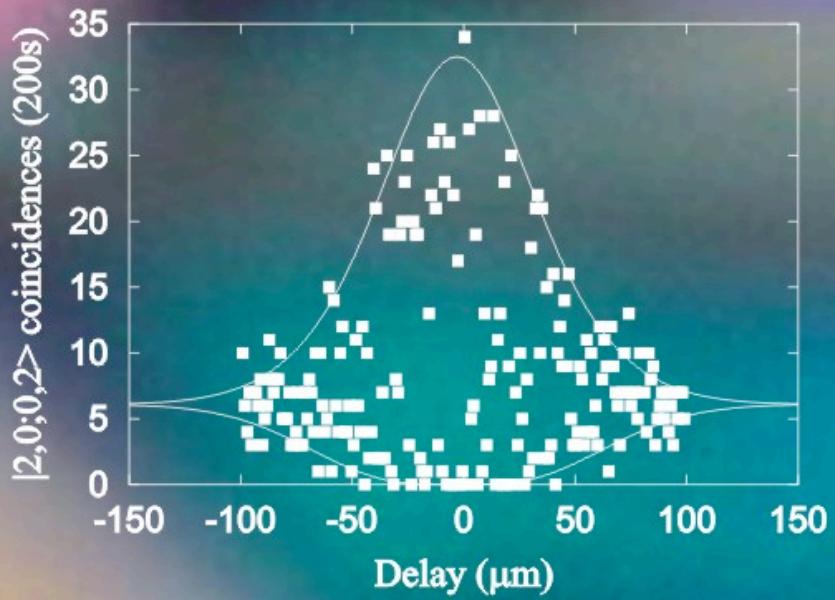
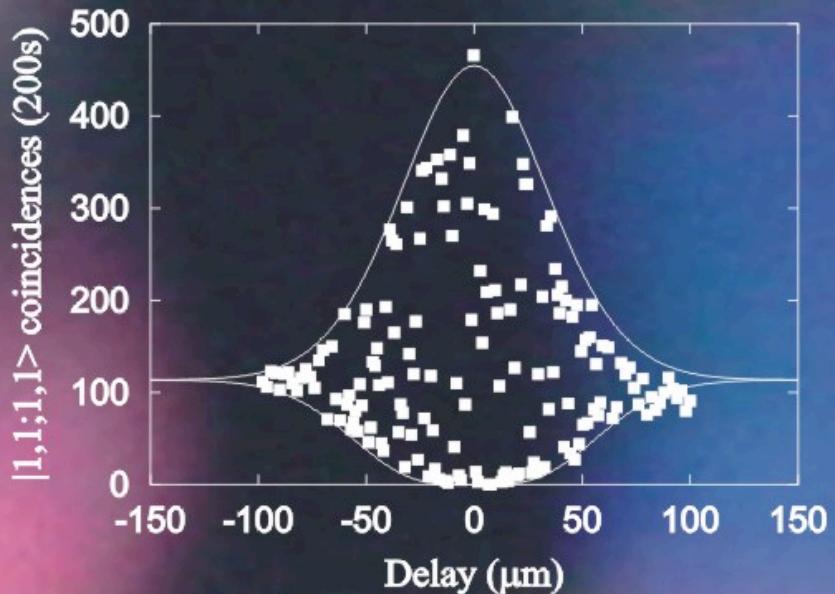
Experimental Set up



Interference Enhanced Bell-State

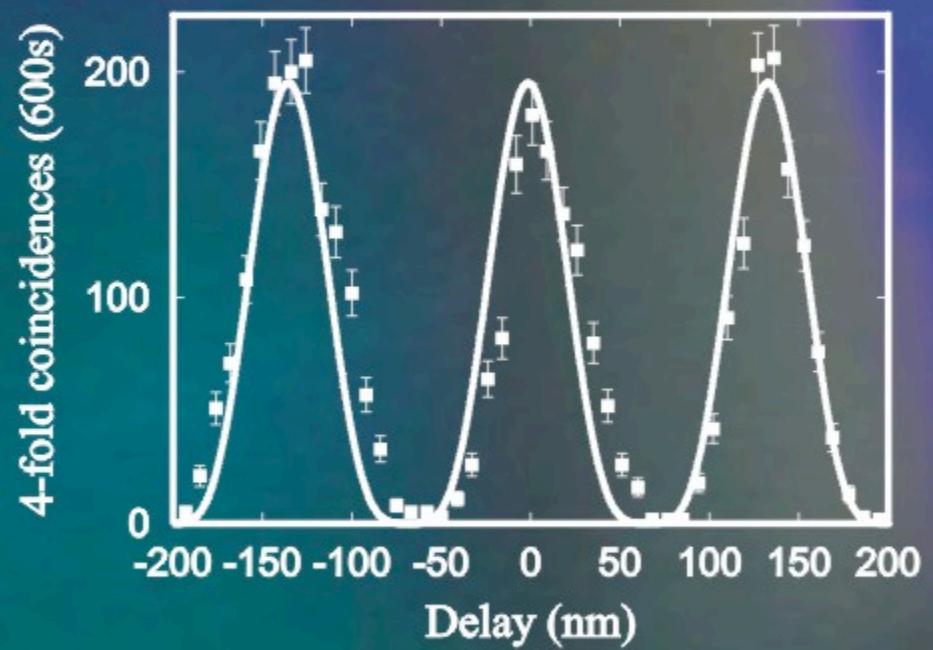


Stimulated Emission of 4-photon state

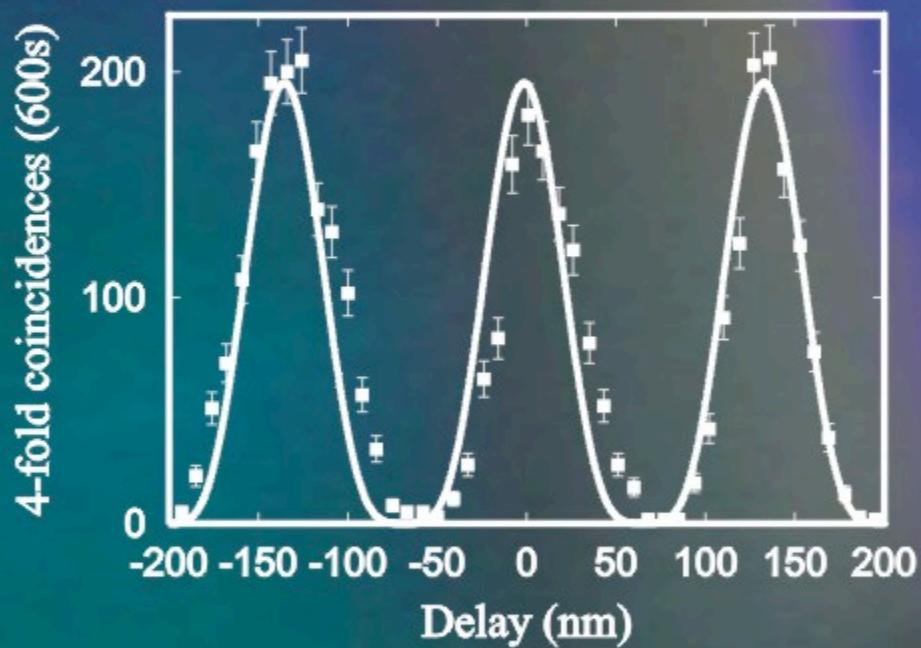


Nature 412, 887 (2001)
A.Lamas-Linares, J. H. Howell, D.B.

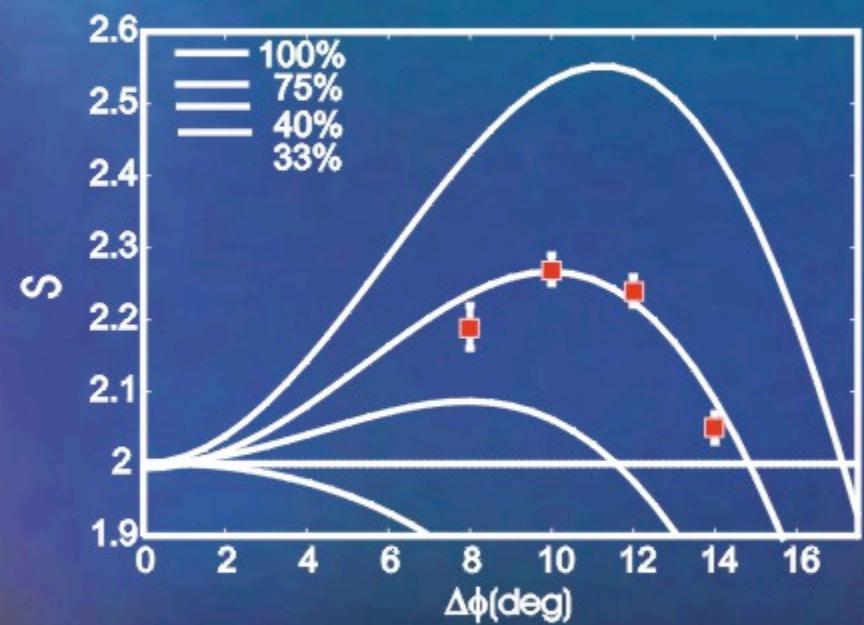
4-Photon Interferometry



4-Photon Interferometry



Spin-1 Bell Inequality Violation



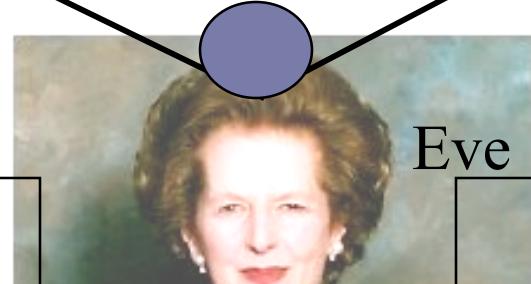
Phys. Rev. Lett. **88** 030401 (2002)
J. H. Howell, A. Lamas-Linares, D.B.

Alice

Eavesdropping

Spin1/2 singlet

Bob



Message

011010111011101

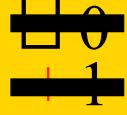
101001010010010

Send

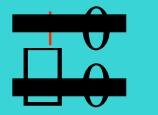
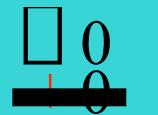
110011101001111

Secret key

101001010010010

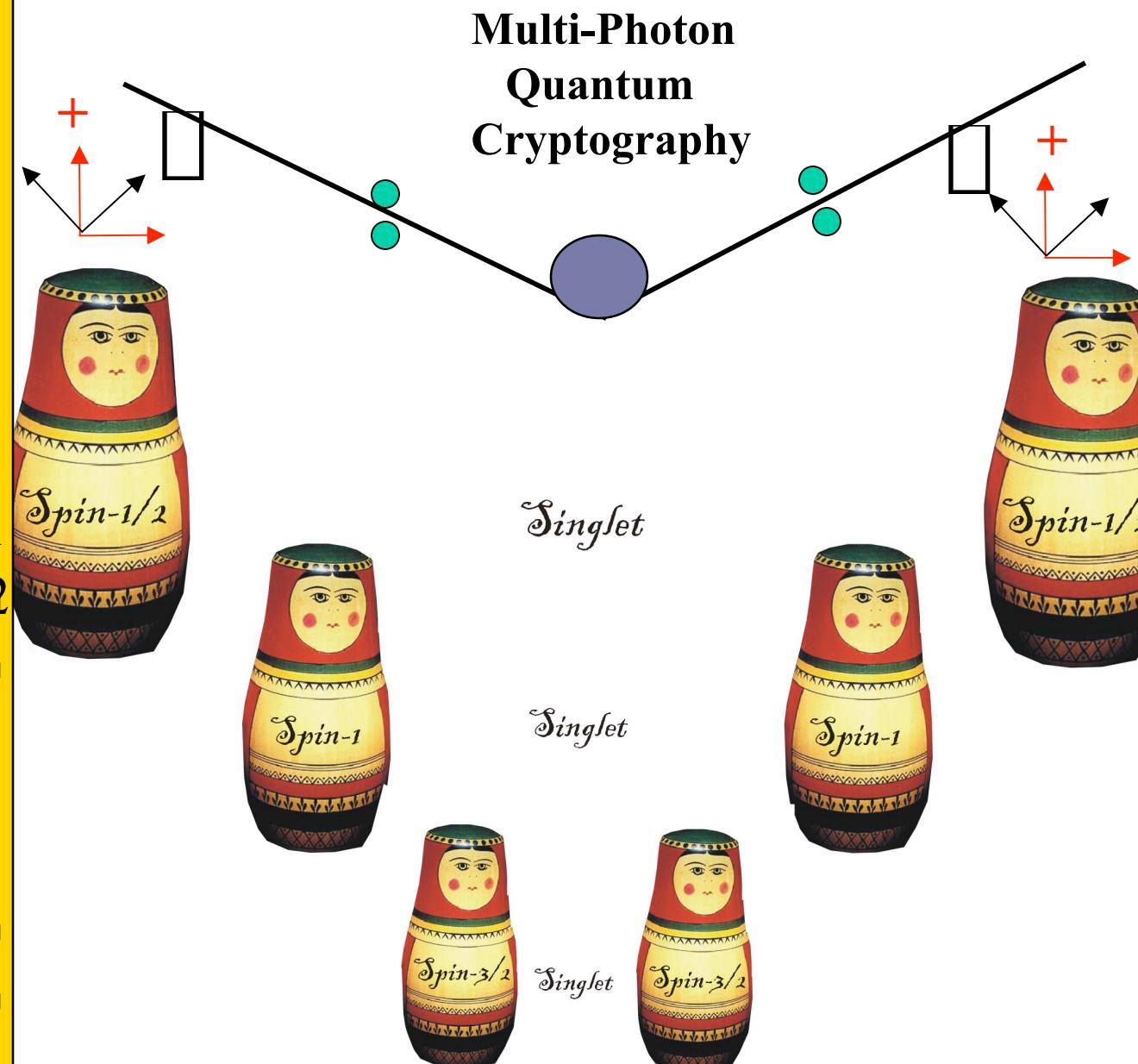


110011101001111
011010111011101



Alice

N_H	N_V	\square
\square	1,0	1
\square	0,2	2
+	2,1	3
\square	1,1	2
+	0,3	3
\square	0,1	1
\square	2,2	4
+	1,2	5
+	0,1	1



Bob

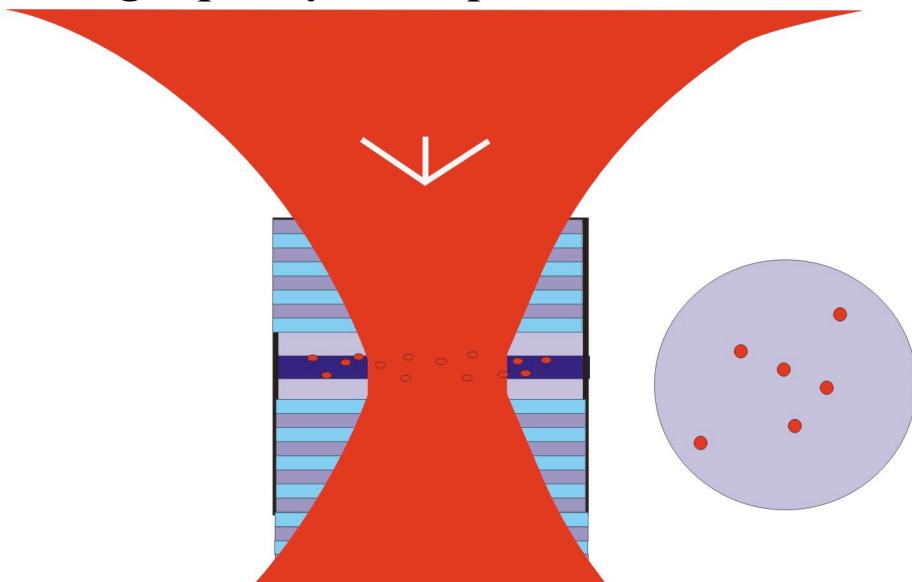
N_H	N_V	\square
\square	0,1	1
+	1,1	2
\square	1,2	3
+	1,1	2
+	3,0	3
\square	1,0	1
+	0,4	4
\square	1,2	3
+	1,0	1

Phys. Rev. Lett. **88**, 187902 (2002)
G. Durkin, C. Simon, D.B.

Quantum Imaging and Metrology needs high-quality multi-photon detectors.

Requirements:

- 90% Efficiency
- @800-900nm
- @1300nm and 1550nm
- At convenient temperatures
- Low background counts
- Fast recovery (<1ns)
- N-photon counting

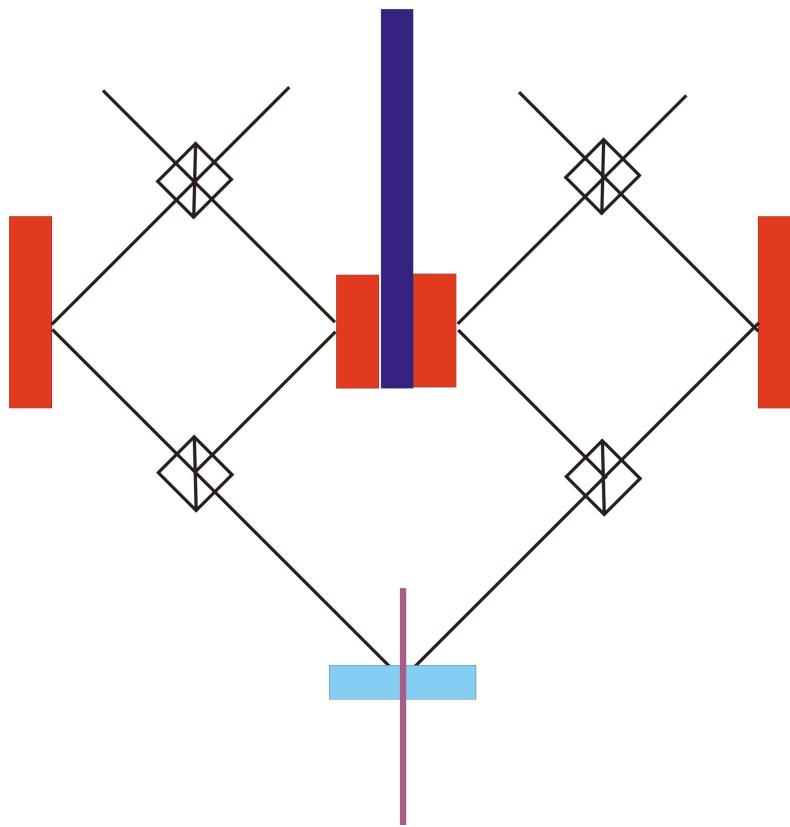


Solution: use ultra small detection volume (virtually no dark counts even at reasonably temperatures, liquid nitrogen or electronic cooling) in optical resonator (to enhance effective cross section). For example Qdot inside micro-pillar including optical waveguiding and Qdot positioning. Collaboration with P. Petroff, E. Hu, L. Coldren, C. Weisbuch UCSB Engineering and Materials Departments.

Solution: N-photon counting use localized “impurity” like inter-band levels. VLPC, Fermi laboratory, new designs UCSB.

Creating Quantum Superpositions of a Tiny Mirror

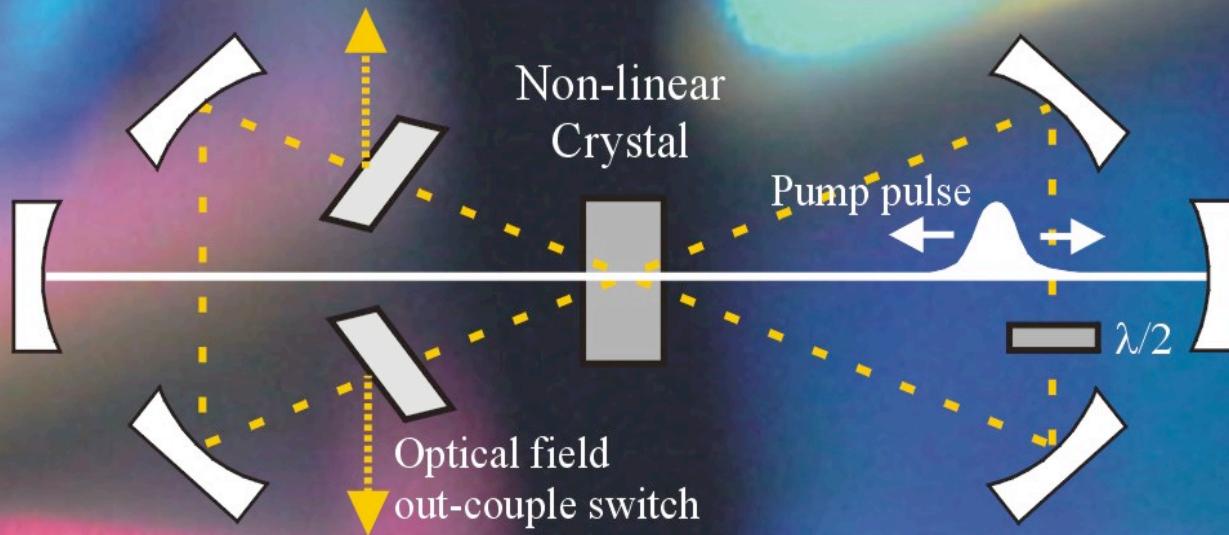
William Marshall, Christoph Simon, Roger Penrose, D.B.



Michelson interferometry: The single photon in right arm will displace the mirror (diameter 10 micron) at the tip of a high quality cantilever. Among the many stringent requirements (see quant-ph) there is the requirement of the initial-state preparation and cooling of the cantilever.

Use correlated photon pairs to measure position of highly sensitive cantilever and apply optical feed-back.

Experimental Set up

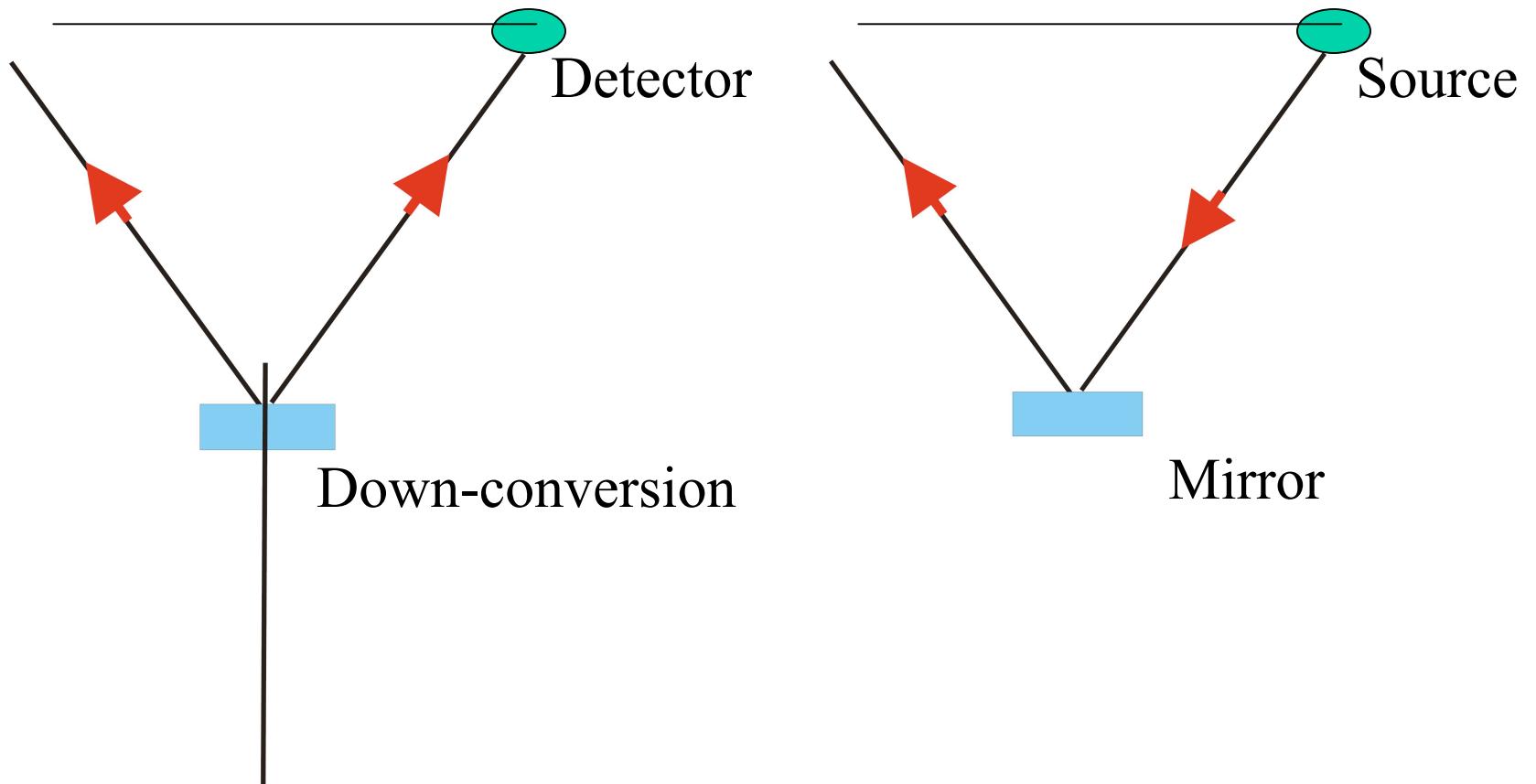


Produce “natural” multi-photon states for applications in quantum cryptography, metrology, error correction and imaging. Going beyond resolution of pump wavelength by using 4 and higher photon states (Microscopy, Biology).

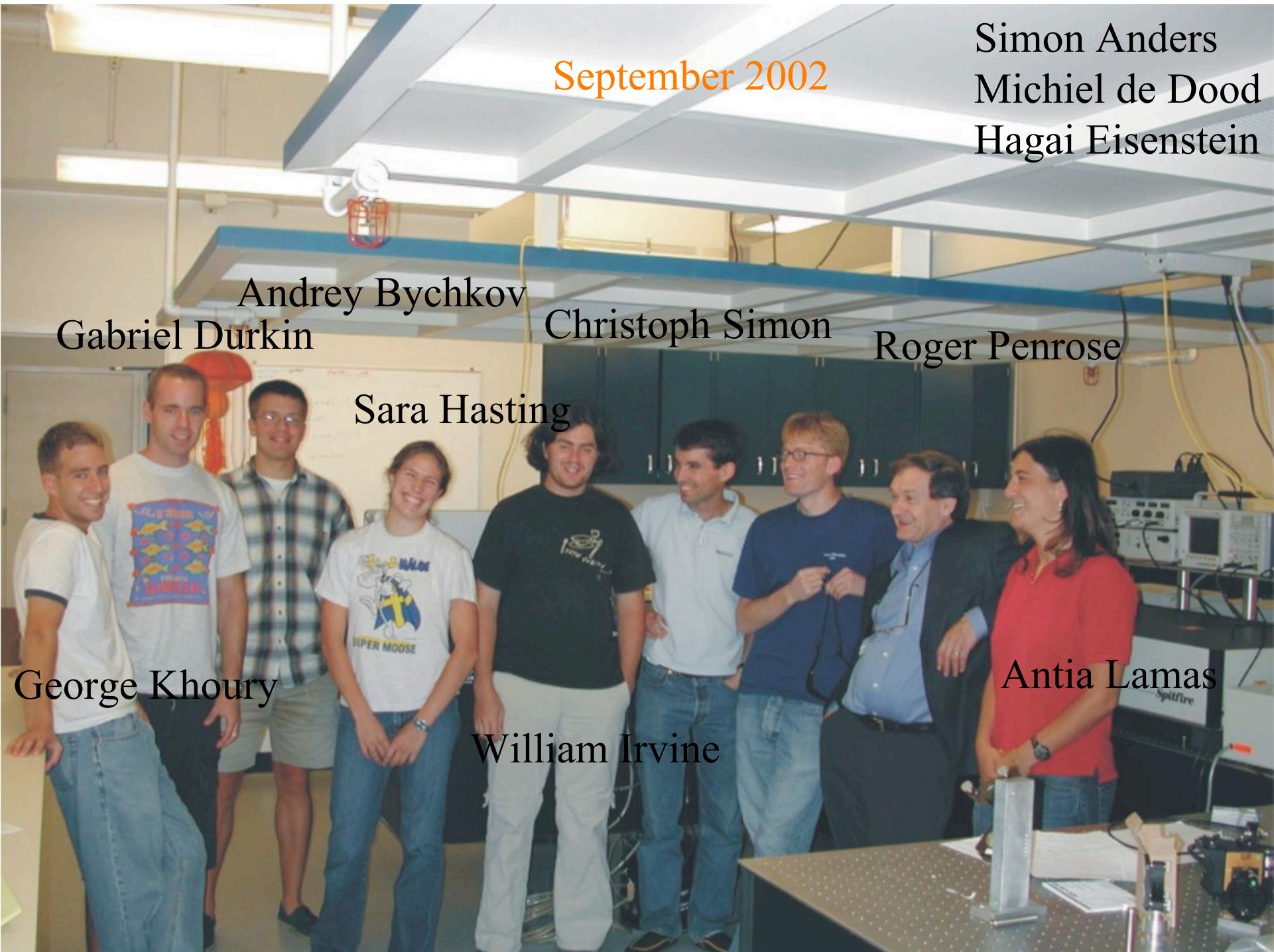
Comment on remote sensing

How remote is remote sensing?

What is real advantage of remote sensing?



Real advantage could be that you can use entanglement purification:
Transmission despite bad quantum channel (single photon path)!



September 2002

Andrey Bychkov
Gabriel Durkin
Sara Hasting
George Khoury
William Irvine
Christoph Simon
Roger Penrose
Antia Lamas

Simon Anders
Michiel de Dood
Hagai Eisenstein